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Design and Development of High Gain Antenna for Mars Orbiter Mission

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Abstract

This paper describes the design and development of High Gain Antenna (HGA) for Mars Orbiter Mission (MOM). High Gain Antenna is required for establishing S-band communication link during Mars Orbit. A Gain of at least 31 dBi is required to establish communication link, when the spacecraft is at distance greater than 40 million km from earth. This figure of Gain of 31 dBi was arrived after link calculation analysis. This Gain can be achieved using aperture type of antennas like either planar array antenna or reflector antenna. This paper describes the reasons for choosing reflector antennas over array antennas. Offset reflector antenna illuminated by conical horn feed was finalised for MOM. This paper subsequently describes the design of offset reflector, the RF characteristics of offset reflector and simulation of secondary pattern. The design of feed, which is required to efficiently illuminate the reflector, is described next. Both the up-link and down-link communication from spacecraft to earth station is by Right Circular Polarisation (RCP); this paper describes the design of septum polariser which is used to generate Right Circular Polarisation. RF measurements were done on HGA at various stages viz. feed level, engineering model of reflector level and FM integrated reflector and feed level. The measured results are described. Finally polarisation check and power level checks of HGA when integrated on satellite were made and In Orbit Tests (IOT) were conducted, these are also mentioned.

Key words: *Mars Orbiter Mission (MOM), Antenna, Offset reflector antenna, feed, conical horn, Septum polariser.*

1. Introduction

High Gain Antenna (HGA) is required for establishing RF communication link at S-band during Mars Orbit. From the link calculations it was established that an antenna of Gain of at least 31 dBi is required, when the spacecraft is away from earth for distances upto 400 million kilometres. HGA bore-sight is mounted along +ve roll of spacecraft, which points towards earth, after 7 million km. The communication from Ground station to Satellite and Satellite to Ground station is in S-band and is in Right Circular Polarisation (RCP). The on-board transmitter power is 250 W and the HGA is required to handle this much power. The detailed specification of MOM HGA is shown in Table-1.

A Peak Gain of 31 dBi can be achieved only by an aperture type of antenna .i.e. either planar array antenna or reflector antenna. Planar array has the advantage that it occupies less volume, but it has other significant disadvantages. 12% required bandwidth is one of the issues, designing an array element which has that much bandwidth is possible using stacked microstrip patch, but this will lead to a very thick size planar array which is very heavy. Power handling of 250 W is also another issue, microstrip feed network cannot handle that much power

Table-1
Specifications of HGA

Sl. No.	Parameters	Specification
1	Frequency	2.05 to 2.35 GHz
2	Polarization	RHCP
3	Return loss	Better than 15 dB
4	Power Handling (D/L)	250 W
5	Gain at boresight	> 31 dBi
6	3 dB full beamwidth	$4.0^0 – 4.2^0$
7	Isolation between the ports	>20dB
8	Life	>3 Years
9	Temperature	-100° C to +100° C
10	RF Interface	WR-340 W/G

and accordingly a combination of transmission medium like squareax / waveguide along with microstrip feed network needs to be used (or implemented). This leads to increased mass and volume. Feed network losses in planar array are high, which in turn will lead to a planar array of larger aperture area to meet the same Gain. In addition design of planar array is complex and takes large design and fabrication time. Reflector antennas do not have the above disadvantages. They are light weight, can handle high power and offset reflectors are foldable and can be made deployable. Reflectors can be classified in number of ways (1) based on surface as paraboloidal or non-paraboloidal, (2) based on number of reflectors like single reflector or dual reflector, (3) based on geometry like prime focus or offset. For Mars Orbiter mission single, offset, paraboloidal reflector was selected based on simplicity, low weight, High Gain and for deploy ability.

The feed illuminating the reflector should illuminate it with high efficiency. This is done by selecting feed dimensions appropriately for required edge taper. The feed should also have low cross-polarisation for high efficiency. The up-link and down-link communication is through RCP; therefore septum polariser is used to achieve RCP. Suitable transitions are also designed from septum polariser to feed and septum polariser to WR-340 waveguide output. Keeping the weight low was one of the most important constraints in the design of all components for HGA of MOM.

2. Design of Offset Reflector

Offset paraboloidal reflector has many advantages over prime focus reflectors [1]. No aperture blockage and therefore no reduction in Gain and no spurious cross-polarisation from feed and struts. Reaction of reflector upon primary feed is negligible as a result primary feed VSWR is independent of reflector. However the greatest advantage especially as satellite antenna is that it can be easily folded and deployed. However, offset reflector has few disadvantages. When illuminated by linearly polarised feed will generate cross-polarisation components. When it is illuminated by circularly polarised feed, beam is squinted from bore-sight. Lower the f/D, more the beam squint and higher the reflector offset angle, the more the beam squints.

Offset reflector of required diameter has been designed to meet required Gain. The offset reflector has approximately the same diameter as those that has been flown in earlier GEOSAT missions, for payload applications. Many aspects of implementation on the spacecraft like the size of the spacecraft, hold down locations, closing angle, feed location determine the optics of the offset reflector. Schematic diagram of the offset reflector geometry is shown in Fig. 1.

Focal length was selected, based on accommodation of reflector and feed in spacecraft. Secondary pattern simulation was done so that for given f/D, the decrease in boresight Gain due to beam squint was acceptable. The RMS requirement of the reflector was computed by using Ruze's formula and RMS accuracy of 0.5 mm (500 microns) was found sufficient. Fig. 2 gives ray optics of reflector antenna. Fig. 3 gives High Gain Antenna, reflector and feed as mounted in spacecraft, from this figure it can be seen that feed is close to Gas Tank. The feed points towards the mechanical centre of the reflector. It was found during simulations of secondary radiation pattern in commercially available reflector analysis software TICRA, that there is not much difference in co-polar gain for a feed pointing towards mechanical centre or electrical centre. However, since the mechanical centre is higher than the electrical centre, it was felt that scattering from gas tank will have lesser effect if feed is pointed towards mechanical centre. The feed in order to point at mechanical centre has to make an angle of 43.02^0 w.r.t. principal axis. The edge angles subtended by feed to reflector are 34.94^0 (lower side) and 28.314^0 (upper side).

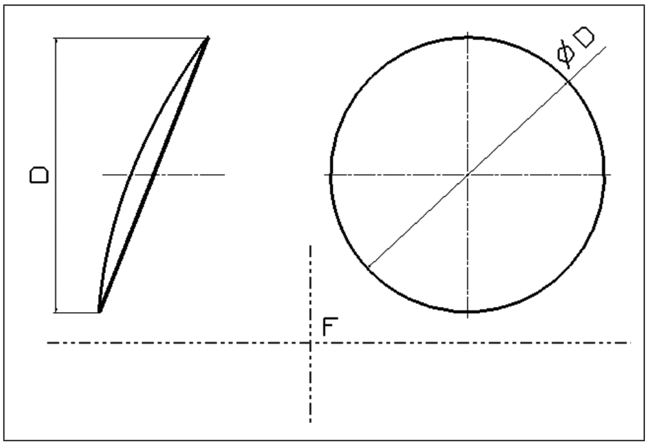

Fig. 1. Schematic of the reflector geometry

Secondary pattern simulations were done in *TICRA*, with simulated and measured feed patterns, as inputs. The feed pointed towards the mechanical centre and made an angle of 43.02^0 with principal axis. There were concerns that Gas Tank placed near vicinity of

feed of HGA would deteriorate the pattern and Co-polar Gain. The effect of multi-path reflections and scattering from this Gas Tank was analysed using Physical Optics (PO), after modelling the same.

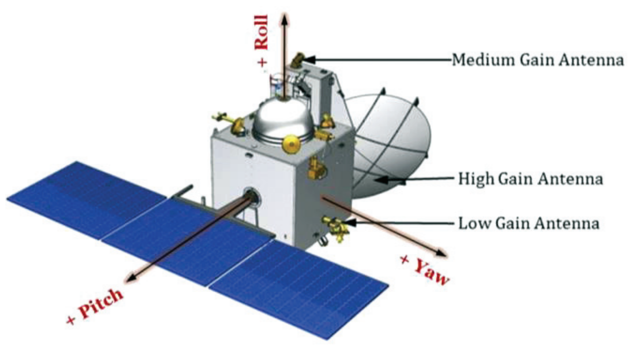

Fig. 2. Reflector ray optics

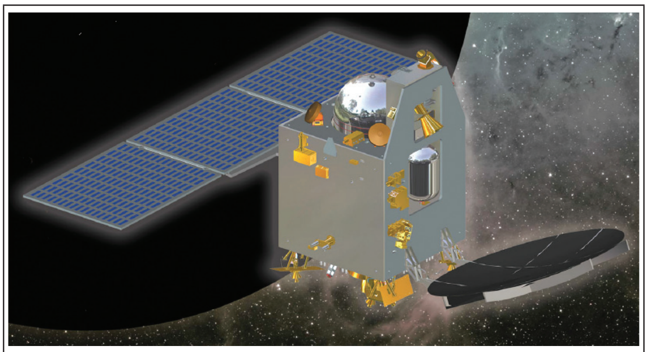

Fig. 3. Reflector and feed as accommodated on the satellite

Gas Tank modelling in vicinity of HGA, which was done in *TICRA* is shown in Fig. 4. The effect of hold-on bolts coming on surface of reflector on radiation pattern was also simulated. The simulated peak gain (after estimating losses) at uplink frequency (2.111 GHz – 2.117 GHz) was 31.7 dBi. The simulated peak gain (after estimating losses) at downlink frequency (2.293 GHz – 2.298 GHz) was 32.4 dBi. The simulated cross-polarisation was -21 dB, as there is no frequency re-use, this is not a concern. An offset reflector, with feed kept at focus, when illuminated with circular polarisation squints the beam away from boresight. The beam squint takes place on plane of symmetry (+ Yaw axis). The theoretical and simulated beam squint was 0.26^0. This angle is too small when compared with 3dB beam width of reflector and therefore it is not a concern. The simulated secondary pattern at 2.111 GHz is shown if Fig. 5.

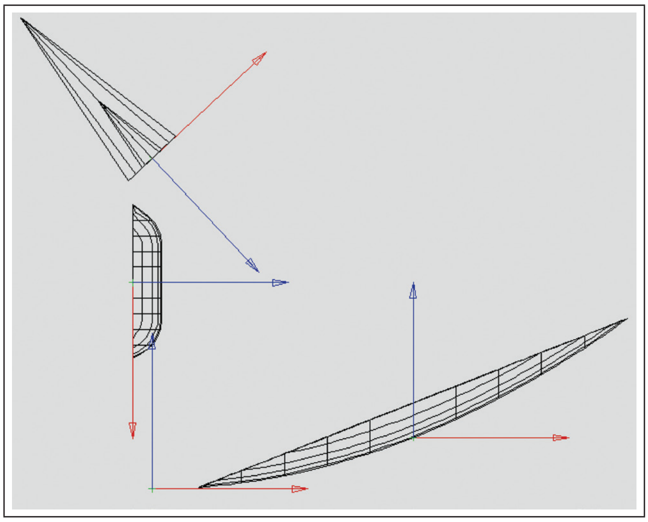

Fig. 4. Gas tank modelling in vicinity of HGA

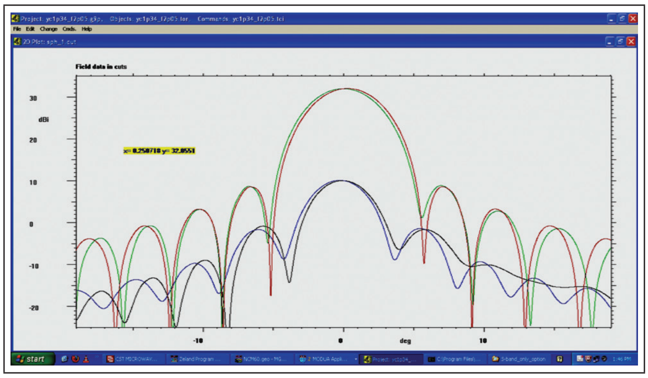

Fig. 5. Simulated secondary pattern at 2.111 GHz

3. Design of feed system

The feed system consists of radiating horn and Septum Polariser connected together with suitable transition. The feed for illuminating the reflector should have desirable characteristics such as beam symmetry and low cross-polarisation. The feed should illuminate the reflector with appropriate Edge Taper of around -8 dB to -12 dB, for good reflector efficiency. Conical horn was selected because these are inherently light weight as compared with corrugated horn. For conical horn with small aperture diameter, the cross polarisation is not very high and beam symmetry is satisfactory [2]. The input waveguide to this horn is a circular waveguide. The feed pattern requirement is to have a 10 dB taper at around 32°, which corresponds to a gain requirement of 13 to 14 dBi. Hence a feed of medium sized aperture diameter of 1.8 λ is sufficient to get this gain values. The other parts for the feed are the square to circular waveguide transition, septum polarizer, 90˚ waveguide bend for the usable port (LHCP port). The RHCP port of septum polarizer is match terminated using load that can handle up to 6W of power. Septum polarizer [3] is used to generate a circularly polarized

wave. This is generated by the superposition of two orthogonal linearly polarized waves that possess identical magnitude and a phase difference of ±90°. This can be obtained by using a septum inside a rectangular waveguide as shown in Fig. 6.

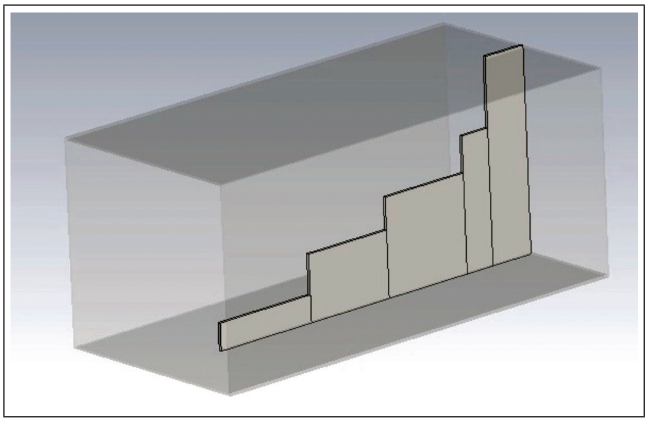

Fig. 6. Schematic of the Septum Polarizer with and stepped transitions

The maximum bandwidth of a square waveguide septum polarizer is limited by the cut-off frequency of the TM_{11} mode. A septum Polarizer has been designed for operating in 2.1 – 2.3 GHz frequency. Since the bandwidth required is less (<10%), a standard septum polarizer with 4 steps is used. The return loss at the LCP port (and also RCP port) of septum polariser should be better than 15 dB, and the isolation between LCP and RCP ports of septum polariser should be better than 20 dB.

The 3D model of HGA feed with conical radiating horn, circular waveguide, transition and septum polarise, which is mounted on mounting bracket is shown in Fig. 7.

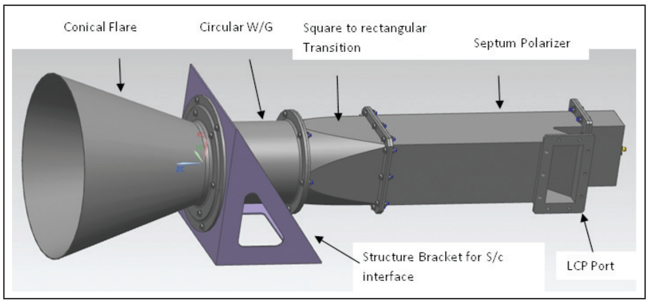

Fig. 7. 3D model of the finalized configuration of the HGA feed with the mounting bracket

Fig. 8 shows simulated and measured return loss of HGA feed for LCP port. It can be seen from this figure that measured return loss is better than 20 dB over required bandwidth. Fig. 9 shows simulated and measured isolation between two ports of HGA feed, it can be seen that isolation between the two ports of septum polariser is good and better than 20 dB.

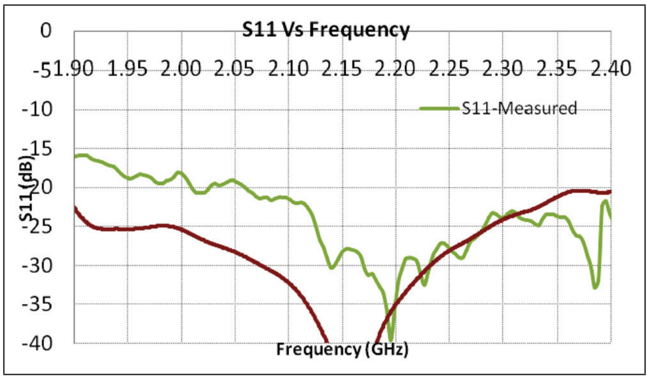

Fig. 8: Simulated vs. measured return loss of HGA feed for LCP port

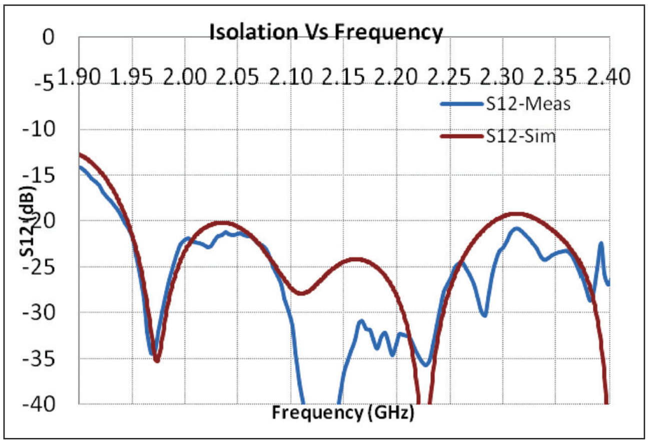

Fig. 9. Simulated vs. measured Isolation between the two ports of HGA feed

The comparison between the simulated and measured Co and Cross polar performance of the HGA feed at 2.1 GHz is shown in Fig. 10. There is a good circular symmetry in the pattern over all the cuts. The edge taper at average taper angle of 32^0 is -9 dB at uplink frequency and -11 dB at down link frequency, which meets requirements.

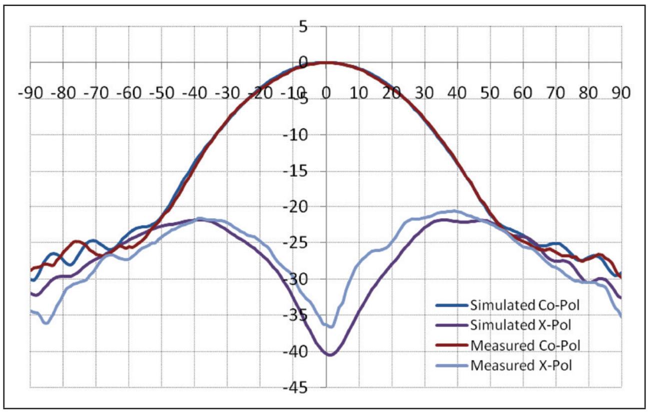

Fig. 10. Comparison of simulated and measured co and cross polarized radiation of feed at 2.1 GHz

4. Measurement of Integrated reflector and feed

An aluminium engineering model of reflector antenna was fabricated and feed was integrated to it and radiation pattern measurements were made in ISAC CATF. The measured radiation pattern, Gain and cross-polarisation of aluminium model were satisfactory. The aluminium model measurements were done to gain confidence and the results are not presented here. The Flight model (FM) consisting of CFRP reflector and feed was integrated and measurements were done at SAC CATF, because of availability of fixture at SAC. Before measurements the feed was aligned very accurately with the reflector, with phase centre of feed (43mm inside the feed axis) coincides with the focus of reflector and feed making angle of 43.02^0 so as to point at mechanical centre of reflector. After feed alignment the HGA was mounted in CATF positioner and radiation pattern and Gain measurements were done. Azimuth and Elevation cuts, both co-polar and cross-polar, were measured at $\pm 20^0$, $\pm 14^0$ respectively in steps of 0.05^0 for uplink (2.111 GHz and 2.117 GHz) and downlink frequencies (2.293 GHz and 2.298 GHz). Azimuth cut is along plane of symmetry of reflector and elevation cut is along plane of asymmetry of reflector. Raster scan patterns (co-polar and cross-polar) were measured in step / scan mode in azimuth and elevation range of $\pm 5^0$ in steps of 0.1^0 and 0.2^0 respectively. Gain measurements were also done for the above mentioned frequencies. For locating the beam peak very accurately, the raster scan range and step size were progressively decreased till minimum step of 0.02^0 was reached. The measured Gain at uplink frequency (2.111 GHz) was 31.7 dBi and at downlink frequency (2.298 GHz) was 32.3 dBi. The aperture efficiency for uplink frequency was 62% and downlink frequency was 60%. The obtained 3dB full beamwidth at uplink frequency was 4.2^0 and at downlink frequency was 4^0. The cross-polarisation (LCP) pattern obtained at up-link and down-link frequencies were -24 dB and -23.8 dB respectively. This cross-polarisation is due to two factors: (a) Cross-polarisation due to conical horn feed itself, which is not a Very Good Huygens's source and (b) Cross-polarisation due to Septum-polariser. Since there is no frequency re-use this much levels of cross-polarisation was acceptable. As expected, there was a beam squint in azimuth plane (plane of symmetry) of approximately 0.25^0. This is because an offset reflector, when illuminated with circularly polarised feed pattern will result in beam squint in secondary pattern along the plane of symmetry of the reflector. The beam squint value of 0.25^0 and the direction of the squint matched with the simulations and computations. The loss in Gain at boresight (mechanical axis), due to beam squint is 0.03 dB. The measured Side Lobe Level were -22 dB and -24 dB, in the plane of asymmetry and symmetry, respectively, the simulated Side Lobe levels were around -23 dB and -25 dB. Peak Gain, 3 dB beamwidth and beam squint, of measured secondary pattern of High Gain antenna, measured at SAC CATF are tabulated in Table-2. Table-3 gives cross-polarised level and 1st Side Lobe Level of measured secondary pattern of High Gain antenna, measured at SAC CATF. The measured radiation pattern at 2.111 GHz, azimuth cut (plane of symmetry) is shown in Fig. 11. Fig. 12 shows photo of High Gain Antenna for Mars Orbiter Mission, mounted on SAC CATF positioner.

Table-2

Peak Gain / 3-dB full beam width / Beam shift of measured secondary pattern of High Gain Antenna, measured at SAC CATF

Frequency (GHz)	Peak Gain (dBi)	3 dB beam width (degrees)		Beam shift (degrees)	
		Azimuth	Elevation	Azimuth	Elevation
2.111	31.66	4.21^0	4.24^0	0.273^0	0.002^0
2.117	31.65	4.19^0	4.23^0	0.225^0	0.020^0
2.293	32.23	3.98^0	4.03^0	0.299^0	0.100^0
2.298	32.19	3.97^0	4.03^0	0.323^0	0.062^0

Table-3
Cross-polarisation / 1st Side Lobe Level of measured secondary pattern of High Gain Antenna, measured at SAC CATF

Frequency (GHz)	Cross-polar Level (dB)		1st Side Lobe Level (dB)	
	Azimuth	Elevation	Azimuth	Elevation
2.111	-24.41	-25.84	-23.93	-21.54
2.117	-24.97	-26.37	-23.78	-21.16
2.293	-23.83	-26.17	-24.57	-21.59
2.298	-23.67	-26.22	-24.56	-21.72

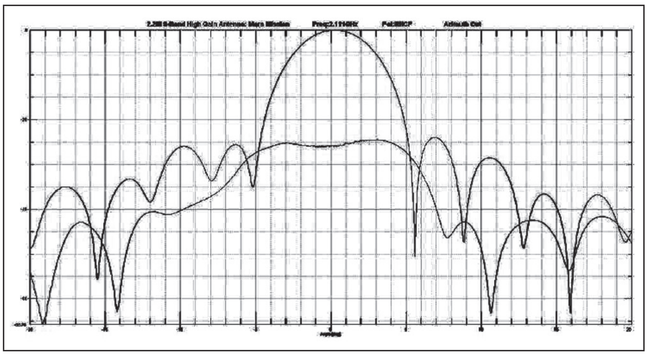

Fig. 11. Measured secondary radiation pattern 2.111 GHz, azimuth cut

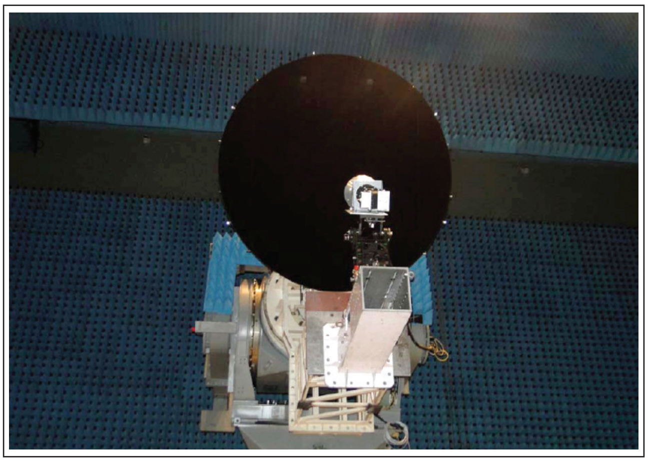

Fig. 12. HGA mounted in SAC CATF positioner

5. Integration of HGA to spacecraft, Integrated Satellite Test (IST) and IOT

The HGA consisting of reflector and feed were separately integrated to spacecraft. The feed was mounted into feed bracket, and feed connected to subsequent WR-340 waveguide routing. Final feed and reflector alignment measurements were done, the reflector was aligned with accuracy of 0.7 mm with respect to Spacecraft coordinate system and feed was aligned with accuracy of 2 mm with respect to reflector. Polarisation verification and power levels radiated from HGA were tested in EMI lab at ISAC and similar verification was done as part of IST at SHAR, these were satisfactory. After launch of MOM, IOT was conducted. Two cuts, one along Roll-Pitch plane the other along Roll-Yaw plane, were taken. Downlink CNDR was measured and uplink receiver power levels were measured and compared with expected values. Polarisation verification and cross-polarisation levels were also measured. After the switch-over to HGA also, the link obtained was as per expectations.

Conclusions

High Gain Antenna (HGA) for Mars Orbiter Mission (MOM) was designed and developed. Radiation pattern measurements, Gain and cross-polarisation measurements were done. This Antenna was flown on MOM and link levels obtained were satisfactory.

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